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Effects of charge temperature and fuel injection pressure on HCCI engine

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Abstract This work investigates the effect of both inlet air temperature and fuel injection pressure on performance and emission behaviour of homogeneous charge compression ignition engine (HCCI) fuelled with diesel fuel. In this investigation, HCCI engine operates with different inlet air temperature and fuel injection pressure, and analysis the effect of these variables on HCCI engine performance and emissions. The inlet air temperatures are varied between 40 °C and 70 °C and the injection pressure in the port fuel injector is varied from 3 bar to 5 bar respectively. From the results, the optimum inlet air temperature and fuel injection pressure for efficient HCCI engine operation are identified. The result shows that, brake thermal efficiency of HCCI is nearer to the value of conventional diesel engine, and can be obtained if HCCI engine operates with 5 bar injection pressure and 60 °C air temperature and a simultaneous reduction in oxides of nitrogen (NOx) and smoke emissions compared to conventional diesel engine. However, when inlet air is heated for improvement of vaporisation of diesel fuel, the higher inlet air temperature limits the operation range of HCCI engine, due to high knocking intensity, high NOx emissions and misfire of charge. The fuel injection pressure is also limited due to high level of HC and NOx emissions.

1. Introduction

1.1. Background

Homogeneous charge compression ignition engine is a promising alternative engine for conventional diesel engine with high power output and low exhaust emissions (NOx and smoke). The HCCI engine has disadvantages of high CO and UHC emissions [1]. In SI and CI engines, the start of combustion timing can be controlled with spark plug and fuel injection timing respectively. But HCCI engine does not have direct methods to control the combustion for best fuel economy and lower emissions. The following parameters, can be used to affect the combustion phase of the HCCI engine, fuel characteristics,

Abbreviations HCCI, homogeneous charge compression ignition engine; NOx, oxides of nitrogen; CO, carbon monoxide; HC, hydrocarbon; BMEP, brake mean effective pressure; BTE, brake thermal efficiency; SFC, specific fuel consumption; SOI, start of ignition; TDC, top dead centre; HSU, hatrige smoke unit; CI, compression ignition; SI, spark ignition; EGR, exhaust gas re-circulation; UHC, unborn hydrocarbon; DI, direct injection; ECU, electronic control unit; N m, Newton metre; CO_2, carbon dioxide; O_2, oxygen

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inlet air temperature, fuel injection pressure, and fuel injection timing. In addition, the engine performance can be influenced by the injector spray geometry, exhaust gas recirculation, variable value timing, swirl ratio and compression ratio [2–5].

One of the main challenges of HCCI engine is to prepare the homogeneous mixture. In HCCI engine, a homogeneous charge is prepared by port fuel injector that injects the fuel on the inlet air stream to form premixed charge. The external mixture formation has the major problem of higher UHC emissions. Ryan and Callahan [6] used an electronic port fuel injector located approximately 15 diameter upstream of the inlet valve; this injector was used for injecting fuel into the intake air for HCCI mode engine operation. The heated intake air and EGR allowed intake temperature up to 240 °C for fuel vaporisation. Odaka et al. [7] used earliest premixed/direct injected system for HCCI operation. In this system, most of the fuel was injected into the intake manifold to form a homogeneous charge and premixed charge was injected with a small amount of fuel directly injected into the cylinder. This system can reduce both NOx and smoke emissions better than conventional diesel engine.

The inlet air temperature is the one of the governing parameters to control and improve the HCCI combustion. The inlet air temperature affects the start of combustion timing and combustion duration; high inlet air temperature advances the start of combustion and reduced the volumetric efficiency of the engine [8]. Ramesh et al. [9] conducted the experiments on a homogeneous charge compression ignition engine using acetylene as a fuel. The inlet air was heated to different temperatures in order to determine the optimum level from the range between 40 °C and 110 °C. The brake thermal efficiency was found to improve with increase in the inlet air temperature, and nitric oxide and smoke levels were reduced. Similarly, Christensen and Johansson [10] used premixed air for achieving HCCI operation. Mancaruso and Vaglieco [11] investigated the combustion behaviour of HCCI engine with different injection pressures such as 400 bar, 500 bar, 600 bar and 700 bar respectively, where rapeseed methyl ester and diesel were injected earlier directly into the cylinder during the suction of the engine. From this investigation, the author resulted that, the exhaust emissions of NOx and smoke were reduced by increasing the injection pressure. At the same time minor reduction in carbon monoxide and HC emissions is obtained due to increase in the injection pressure. From the literature survey, it is identified that increasing the inlet air temperature is the effective method for HCCI combustion control; however, increasing the fuel injection pressure can improve the power output and may reduce the exhaust emissions.

1.2. Objective and motivation

Homogeneous charge compression ignition engine is having an advantage of ultra low NOx and smoke emissions. The main difficulty to achieve HCCI combustion is to control the start of ignition timing. The main scope of this study was to improve HCCI engine performance and reduce emissions by varying the charge temperature and fuel injection pressure. The inlet air temperature can further improve the charge to be more homogeneous and raise the in-cylinder temperature. The fuel injection pressure is accelerating the fuel penetration percentage; high fuel injection pressure improves atomisation of fuel. Hence, these two parameters can improve HCCI engine performance and reduce exhaust emissions. The main objective of this research is identifying the required inlet air temperate and optimum fuel injection pressure for efficient HCCI operation, and analysing the effect of inlet air temperature and fuel injection pressure on diesel fuelled HCCI engine.

2. Experimental setup

2.1. Fuel injection system

Homogeneous charge compression ignition engine uses port and direct fuel injection systems. The port fuel injection is mainly for creating the homogeneous mixture, which is fully controlled by electronic control unit (ECU). The specifications of port fuel injector are listed in Table 1. The amount for fuel injection and fuel injection timing is controlled by ECU depends on engine speed and load conditions. The in-cylinder injection is used to ignite the homogeneous charge, which is controlled by mechanical operated pump, and the main injector injects the small amount of diesel fuel at a constant pressure of 150 bar.

2.2. Experimental setup and procedure

A single cylinder, four stroke, water-cooled, DI diesel engine was used in this research work. The specifications of the modified Kirloskar SV1 engine are listed in Table 2. Fig. 1 shows the experiment setup of HCCI mode engine. An electrical heater is coupled with engine suction pipe and air temperature

Table 1 Port fuel injector specifications.

Parameters	Specification
No of nozzles	4
Nozzle diameter	0.25 mm
Injection pressure	1–50 bar
Made	Hyundai
Mode of control	Electronic controlled

Table 2 Engine specifications.

Sl. No	Parameters	Specification
1.	Make and model	Kirloskar SV1
2.	General details	Single cylinder, four stroke, water cooled, port injection
3.	Bore	87.5 mm
4.	Stroke	110 mm
5.	Cubic capacity	0.661 l
6.	Rated output	5.9 kW at 1800 rpm
7.	Compression ratio	17.5: 1
8.	Inlet valve open BTDC	4.5 Deg.
9.	Inlet valve close ABDC	35.5 Deg.
10.	Exhaust valve open BBDC	35.5 Deg.
11.	Port fuel injection timing (BTDC)	10 Deg.
12.	Direct fuel injection timing (ATDC)	10 Deg.

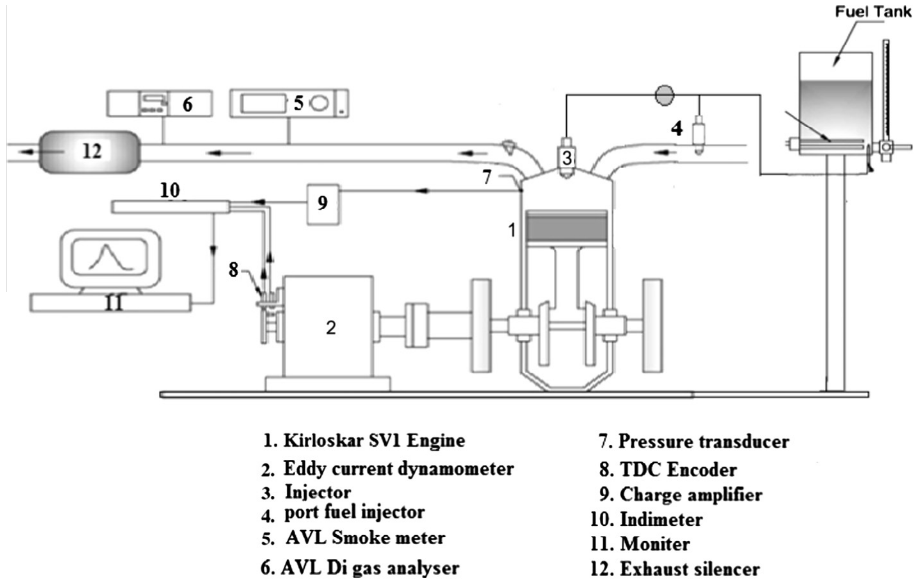

Figure 1 Experimental setup of Kirloskar SV1 engine.

Table 3 Instrument range and accuracy.

Sl. No	Instrument	Range		Accuracy
1	AVL Di Gas analyser	CO	0–10%	±0.02
		CO_2	0–20%	±0.03
		HC	0–1000 ppm	±20 ppm
		NOx	0–500 ppm	±10 ppm
2	AVL Smoke meter	0–100 opacity in %		±2%
3	Dynamometer controller	Load indicator	0–40 N m	±0.2
		Speed indicator	0–2000 rpm	±10 rpm
4	Thermocouple			±1 °C
5	Burette for fuel measurement			±0.1 cc
6	Manometer			±1 mm
7	Pressure transducer			±0.3 kg
8	Crank angle encoder	0–110 bar		±1

is controlled by ECU. The fuel injection timing was controlled by using electronic controlled unit.

One end of engine shaft is coupled with eddy current dynamometer for applying the load. The dynamometer is controlled by manually in the control penal; it is placed separately near to the test engine and it is having a roller nab by using this and can change the load on the engine. The applying load on the engine is shown in N m on digital meter. The test engine was maintaining the constant speed of 1800 rpm for all loads condition. The speed of the engine is shown in digital meter in the control panel. Engine cooling water inlet and outlet temperatures are measured by using thermo couple. The fresh charge temperature and engine exhaust gas temperature were measured by thermal sensor (T_2 and T_3). All temperature sensors are connected into control panel; these readings are displayed in digital meter. AVL Di-gas analyser was used to measure the exhaust emission from the HCCI mode engine such as CO, HC, NOx, CO_2 and O_2. Accuracy and operating range of this equipment are shown in Table 3. The exhaust smoke was measured by AVL smoke meter. In Table 3, the accuracy and operating range of Smoke meter are listed.

Table 4 Instrument uncertainty.

Measured parameter	Uncertainty in percentage (%)
Specific fuel consumption	±1.5
Brake power	±0.5
Brake thermal efficiency	±1
NO Emission	±4.1
CO emission	±1.5
HC emission	±2.1
Cylinder peak pressure	±0.5

Table 4 provides values about operating range and accuracy of di gas analyser and smoke meter.

Initially the engine has operated with no load condition, to achieve the saturated engine temperature. The experimental investigations have been carried to maintain a different inlet temperature ranges such as 40 °C, 50 °C and 60 °C with constant engine speed of 1800 rpm. The experimental readings were observed from the instruments used in this research and registered the experimental readings based on instrument

Table 5 Properties of reference diesel.

Properties	Diesel
Density @ 15 °C in gm/cc	0.8344
Specific gravity @ 15°/15 °C	0.8360
Kinematic viscosity @ 40 °C (mm^2/s)	3.07
Flash point (°C)	60
Fire point (°C)	69
Cloud point (°C)	15
Calorific value (kJ/kg)	44,125
Cetane number	51

accuracy. The physical and chemical properties of reference diesel are listed in Table 5. The electrical heater is used to control or increase the inlet charge temperature. The fuel injection timing is totally controlled by ECU and depends on the load and engine speed can change the injection timing and injection duration. The speed sensor or optical sensor is adopted near the engine crankshaft used to identify the engine speed and position of piston inside the cylinder. The sensor output is feed to ECU and depends on the signal and the ECU can change the fuel injection time and injection duration.

3. Result and discussion

Brake thermal efficiency is calculated by dividing the actual brake power produced by the engine to the amount of fuel consumed. The brake thermal efficiency of HCCI engine slightly drops compared to conventional diesel engine [6]. Fig. 2 shows, variation in brake thermal efficiency with different inlet air temperature operated HCCI engine, where HCCI engine operates constant fuel injection pressure of 4 bar. From Fig. 2, it is observed that brake thermal efficiency of HCCI engine is increased with increasing the inlet air temperatures between 40 °C and 60 °C. At beyond 60 °C inlet air temperature, the engine drops its brake thermal efficiency due to poor engine volumetric efficiency and misfiring charge [8]. At 60 °C charge temperature, the operated HCCI engine shows maximum brake thermal efficiency as compared to other inlet air temperatures at 4 bar injection pressure and the value of BTE is almost near to the BTE of conventional diesel engine.

The conventional diesel engine produces 25% of BTE at 3 bar BMEP, and similar condition 60 °C inlet air temperature operated HCCI engine produced 22.7% brake thermal efficiency. However, 40 °C inlet air temperature operated HCCI engine produced 20% BTE value at same operating condition. The raise in BTE is about 2.7% for 60 °C air temperature operated HCCI engine. The reason behind this is, the inlet air temperature is an important parameter for creating the homogeneous mixture. An increasing inlet air temperature is used to improve fuel vaporisation and create more homogeneity air/fuel charge slightly reduces the start of ignition (SOI) timing [8]. The SOI timing is varied dependently on fuel injection pressure and inlet air temperature. Hence, higher inlet air temperature may then promote more complete combustion and increase peak in-cylinder temperature.

Variation in BTE for 5 bar injection pressure and different inlet air temperature operated HCCI engine is shown in Fig. 3. Comparing Figs. 2 and 3, both causes HCCI engine to operate at same inlet air temperatures such as 40 °C, 50 °C and 60 °C respectively. But fuel injection pressure can change as 4 bar and 5 bar. From Fig. 3, it is observed that brake thermal efficiency of HCCI engine can improve further by increasing the fuel injection pressure [11], when HCCI engine operates with 5 bar pressure and 60 °C inlet air temperature shows higher BTE values compared to 4 bar injection pressure operated engine.

The fuel injection pressure is one of the governing parameters for HCCI engine power output and exhausts emissions. Higher fuel injection pressure improves fuel atomisation and penetration ratios. Hence, premixed charge of 5 bar injection pressure is more homogeneous than 4 bar injection pressure operated engine. However, fuel injection pressure also makes an impact on SOI timing, if increasing the fuel injection pressure may advance SOI timing and reduce combustion duration [11]. In general, the combustion process takes place only after TDC, and the combustion rate will be improved because of the volume increase during the combustion process. In this study, the fuel injection pressures have been varied between 4 and 6 bar. If HCCI engine operates at 6 bar fuel injection pressure, it reduces BTE and emits higher exhaust emissions. The reason is, due to high injection pressure, the start of ignition is more advanced and combustion will be happened before the TDC.

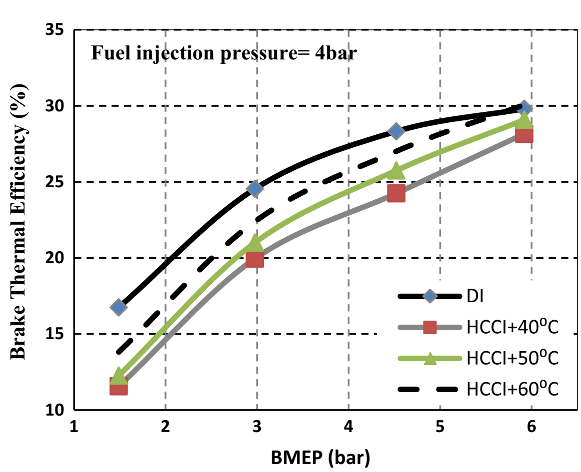

Figure 2 Variation in BTE for different inlet air temperatures, 4 bar injection pressure HCCI engine.

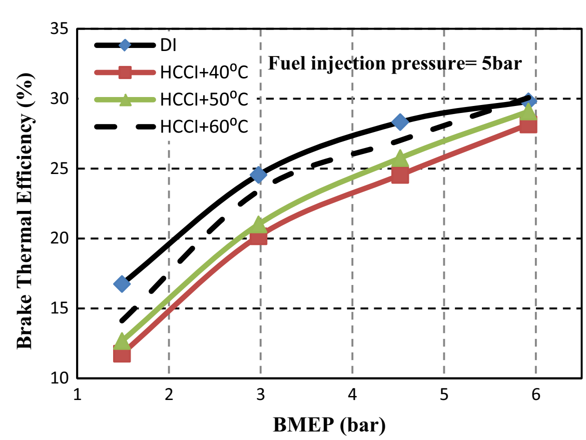

Figure 3 Variation in BTE for different inlet air temperatures, 5 bar injection pressure HCCI engine.

The advanced combustion leads to incomplete combustion and reduced combustion efficiency. Due to this reason, the tests were restricted between 4 bar and 6 bar and resulted in best diesel fuelled HCCI operations.

Low oxides of nitrogen emission are one of the advantages of HCCI engine. In this study, analysing the formation of NOx in HCCI engine operates with different air temperatures and fuel injection pressure. Fig. 4 shows, variation in NOx emission with BMEP's of HCCI engine. Here HCCI engine operates at different inlet air temperatures with constant fuel injection pressure of 4 bar. As seen in Fig. 4, 40 °C inlet air temperature operated engine shows low NOx emission values compared to conventional diesel engine, and values are 60 ppm, 110 ppm, 230 ppm, and 450 ppm. At 5.86 BMEP, HCCI engine shoots up NOx emission to 450 ppm due to at full load operation, and the engine operates using more amount of fuel injected from the in-cylinder main injector and very small amount of fuel injected via port fuel injector. The conventional diesel engine could emit the NOx emissions between 230 ppm and 980 ppm, but diesel fuelled HCCI engine limits the NOx emission from 30 ppm to 420 ppm. The NOx reduction is about 20%, 60%, 80% and 40% for 1.4 BMEP, 2.9 BMEP, 4.5 BMEP, and 5.9 BMEP respectively. The reason for low NOx emission from HCCI engine is that HCCI engine operates with lean air–fuel charge for all operating conditions and combustion starts more or less simultaneously in the entire cylinder at the same time. Hence the HCCI engine eliminated high temperature region and high concentration region, and combustion, and temperature is low compared with conventional diesel engine [1].

Fig. 4 also indicates NOx emission raises with increasing the inlet air temperature. The NOx formation very strongly depends on the combustion temperature, at the combustion temperature over 1800 K, and NOx formation rate increases rapidly with increasing the inlet air temperature. Variation in NO_X formation from HCCI engine, operates with constant pressure and different inlet air temperature is shown in Fig. 5. Fig. 5 shows, NOx formation raises with increasing the fuel injection pressure, where HCCI engine was operated with 5 bar fuel injection pressure. As seen in Fig. 5, the NOx values slightly increase for 40 °C, 50 °C, and 60 °C air temperature operated engine compared to Fig. 4, and the raise in NOx emission is about 2%, 5% and 9%. The fuel injection pressure is one of the factors for increasing the NOx formation. The higher fuel injection pressure increases fuel atomisation and penetration ratios, thereby increasing the homogeneity of the charge [11]. These factors lead to improving the combustion efficiency and increasing the in-cylinder temperature. This is the main reason for increase in NOx emissions, while increasing the inlet air temperature.

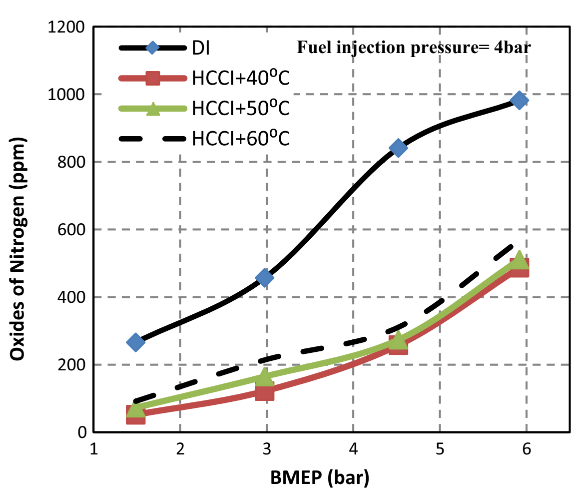

Figure 4 Variation in NOx for different inlet air temperatures, 4 bar injection pressure HCCI engine.

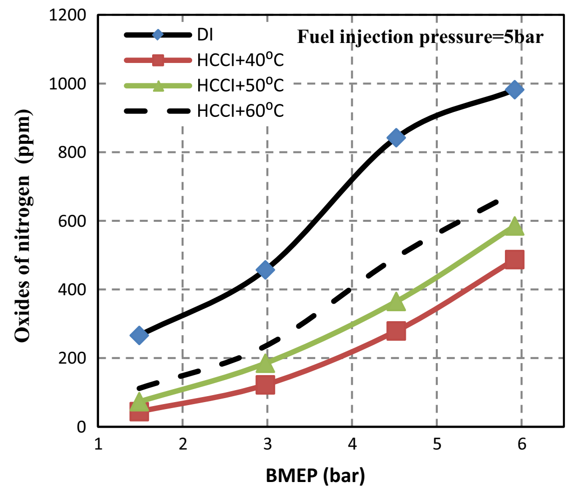

Figure 5 Variation in NOx for different inlet air temperatures, 5 bar injection pressure HCCI engine.

Homogeneous charge compression ignition engine has emitted low smoke density compared to conventional diesel engine due to the absence of rich fuel region [1]. Variation in smoke density from HCCI engine operates with constant fuel injection pressure with different inlet air temperatures shown in Fig. 6. Fig. 6 shows, HCCI engine operating with 4 bar injection pressure and 50 °C inlet air temperature resulted in low smoke emissions compared to other inlet air temperature operated engine. The HCCI engine emits the smoke emission maximum of 32 HSU, but conventional diesel engine emitted smoke density from 36 HSU to 73 HSU. The reduction in smoke density is about 20%, 30%, 35% and 42% at 1.4 BMEP, 2.9 BMEP, 4.5 BMEP, and 5.9 BMEP respectively.

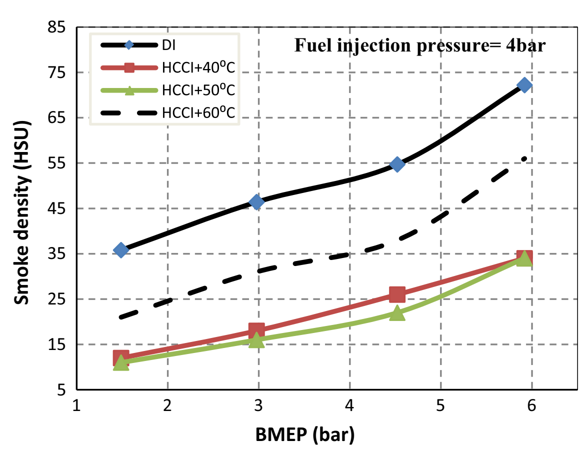

Figure 6 Variation in smoke density for different inlet air temperatures, 4 bar injection pressure HCCI engine.

The reason for low smoke emission is due to the absence of rich fuel pocket inside the combustion chamber. HCCI engine uses lean air–fuel charge and combustion takes place at multiple points in the combustion chamber at the same time, which eliminates rich fuel region [2], due to that, HCCI engine has low smoke emissions than the conventional diesel engine.

Fig. 7 shows, variation in smoke density with 5 bar fuel injection pressure operated HCCI engine. As shown in Fig. 7, the smoke density increases with increasing fuel injection pressure and inlet air temperature, due to partial combustion and advanced start of ignition. The higher fuel injection pressure and inlet air temperatures improve the charge as more homogeneous. If the charge has more homogeneity, it reduces start of ignition timing and decreases the combustion duration. Due to this reason, combustion might take place before the piston reaches TDC position. The earlier start of ignition prevents the combustion process and leads to incomplete combustion. These reasons are favour for high smoke density. The 5 bar fuel injection pressure operated HCCI engine resulted in high smoke density for 40 °C, 50 °C and 60 °C inlet air temperature engine compared to 4 bar injection pressure operated HCCI engine. From the figure, it is observed that, increasing inlet air temperature shoots up smoke density. The percentage of raise in smoke density is 2%, 4% and 5% for 40 °C, 50 °C and 60 °C air temperature operated engine.

Figs. 8 and 9 show, variation in CO emissions for different injection pressure and inlet air temperature operated HCCI engine. Carbon monoxide is one of the important emissions from the HCCI engine, which has high CO emission compared to conventional diesel engine [6]. In HCCI engine, CO is produced during the combustion process by depending on combustion temperature and mixture homogeneous. From the Figs. 8 and 9, it is observed that the amount of CO is emitted by diesel fuelled HCCI engine that was reduced with increasing fuel injection pressure and inlet air temperature. 5 bar injection pressure operated HCCI engine shows low CO emission for three different inlet air temperatures. As seen in the Fig. 9 60 °C inlet air temperature and 5 bar injection pressure operated HCCI engine has low CO emissions compared to other inlet air temperature operated HCCI engine.

The reduction in CO is about 4% than compared to 40 °C air temperature operated HCCI engine for all operating

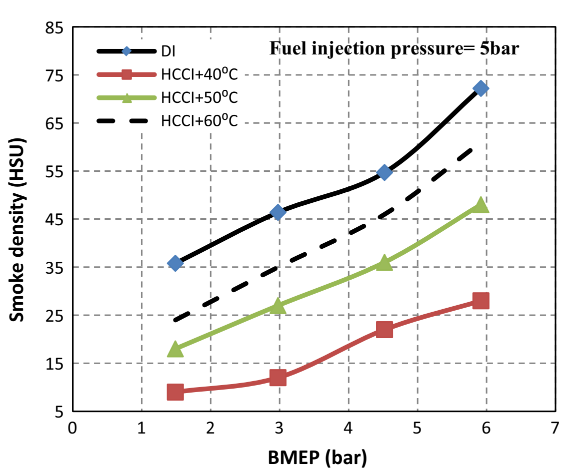

Figure 7 Variation in smoke density for different inlet air temperatures, 5 bar injection pressure HCCI engine.

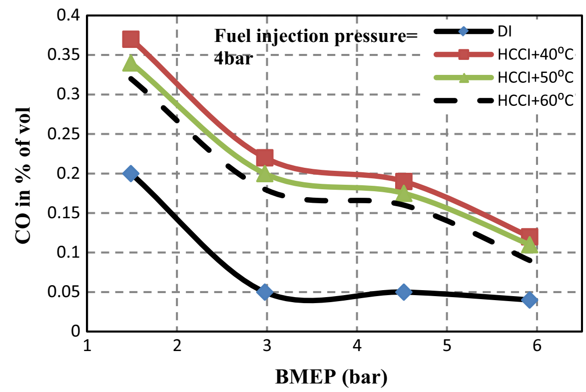

Figure 8 Variation in CO for different inlet air temperatures, 4 bar injection pressure HCCI engine.

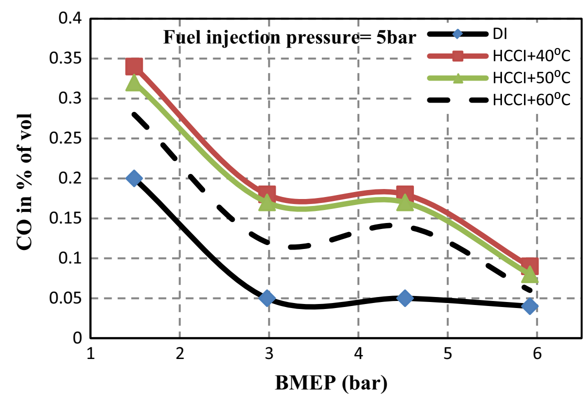

Figure 9 Variation in CO for different inlet air temperatures, 5 bar injection pressure HCCI engine.

conditions. CO emission is decreased with increasing the BMEP's, at low load conditions and HCCI engine exhausted high CO emission and decreased at high load conditions, nearer to conventional diesel engine value. The primary reason for CO formation in HCCI engine is due to low combustion region such as boundary layer near the cylinder wall which causes the CO formation [6]. If the engine load is increased, the combustion temperature and in-cylinder temperature are being increased [4]. These factors lead to reduce the CO emissions at high load operated HCCI engine.

Variation in hydrocarbon for different operating conditions of diesel fuelled HCCI engine are show in Figs. 10 and 11. The figures show, the value of HC emitted by HCCI engine is very much high compared to conventional diesel engine. Figs. 10 and 11, show amount of HC emission emitted by HCCI engine with different fuel injection pressures as 4 and 5 bar, and different inlet air temperatures such as 40 °C, 50 °C and 60 °C. From the figures, it is observed that there is no major difference in HC emissions by varying the fuel injection pressure. But there is slightly reduction in HC emissions by increasing the inlet air temperature between 40 °C and 60 °C, and beyond that inlet air temperature HC emissions have been shooting up due to poor combustion efficiency. The high HC emission from HCCI engine, results in incomplete combustion, which occurs due to low combustion temperature and due to earlier start of combustion.

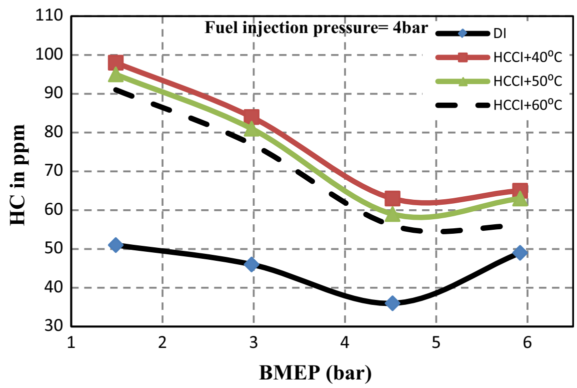

Figure 10 Variation in HC for different inlet air temperatures, 4 bar injection pressure HCCI engine.

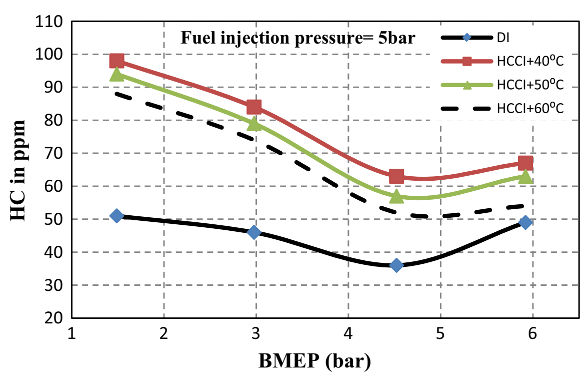

Figure 11 Variation in HC for different inlet air temperatures, 5 bar injection pressure HCCI engine.

4. Conclusion

In this paper, the combined effects of inlet air temperature and fuel injection pressure on performance and emission characteristics of diesel fuelled HCCI engine were studied. From the results, optimum inlet air temperature and required fuel injection pressure for efficient HCCI engine are identified. Results of this work can be summarised as follows:

1. Brake thermal efficiency was decreased in diesel fuelled HCCI engine compared to conventional diesel engine. In addition, BTE is increased with increasing the inlet air temperature and fuel injection pressure within a limit. The 5 bar injection pressure and 60 °C operated engine shows maximum brake thermal efficiency.
2. HCCI engine has very low NOx emissions compared to conventional diesel engine due to lean air/fuel charge and low combustion temperature. 4 bar injection pressure and 40 °C air temperature HCCI engine resulted in low NOx emissions compared to other conditions operated HCCI engine. From this study, it is concluded that the NOx emissions were increased with raising air temperature.
3. Low smoke density is also the advantage for using HCCI engine, and in this study diesel fuelled HCCI engine resulted in low smoke values between 8 HSU and 24 HSU. 5 bar injection pressure, 40 °C inlet air temperature and 4 bar injection pressure, 50 °C inlet air temperature operated HCCI engine resulted in low smoke density values.
4. HCCI engine has resulted in high CO emissions compared to conventional diesel engine, which could be reduced by raising the inlet air temperature and injection pressure. 5 bar injection pressure and 60 °C inlet air temperature operated HCCI engine was shown low CO values for all operating conditions.
5. It is found that hydrocarbon emissions from HCCI engine were reduced by improving the inlet air temperature and injection pressure. In general, HC emission from HCCI engine was higher than conventional diesel engine due to lean premixed charge leads to partial combustion at certain location in the combustion chamber. 5 bar fuel injection pressure and 60 °C inlet air temperature operated HCCI engine resulted in low HC emissions compared to other operating conditions of HCCI engine.

References

[1] K. Epping, S. Aceves, R. Bechtold, J. Dec, The potential of HCCI combustion for high efficiency and low emissions, SAE Paper 2002-01-1923, 2002.
[2] M. Christensen, B. Johansson, Influence of mixture quality on homogeneous charge compression ignition, SAE Paper 982454, 1998.
[3] L. Xingcai, J. Libin, M. Junjun, H. Zhen, Experimental study on the cycle-by-cycle variations of homogeneous charge compression ignition combustion using primary reference fuels and their mixtures, Proc. Inst. Mech. Eng. – Part D J. Automob. Eng. 221 (2007) 859–866.
[4] S. Tanaka, F. Ayala, J.C. Keck, J.B. Heywood, Two stage ignition in HCCI combustion and HCCI control by fuels and additives, Combust. Flame 132 (2003) 219–239.
[5] M. Yao, Z. Zheng, H. Liu, Progress and recent trends in homogeneous charge compression ignition (HCCI) engines, Prog. Energy Combust. Sci. 35 (2009) 398–437.
[6] T.W. Ryan, T.J. Callahan, Homogeneous charge compression ignition (HCCI) of diesel fuel, SAE Paper No. 961160, 1996.
[7] M. Odaka, H. Suzuki, N. Koike, H. Ishii, Searching for optimizing methods of homogeneous charge diesel combustion, SAE Paper 1999-01-0184, 1999.
[8] R.K. Maurya, A.K. Agarwal, Experimental investigation on the effect of inlet air temperature and air–fuel ratio on cycle to cycle variation of HCCI combustion and performance parameter, Appl. Energy 88 (2011) 1153–1163.
[9] A. Ramesh, S. Swami Nathan, J.M. Mallikarjuna, An experimental study of the biogas–diesel HCCI mode of engine operation, Eng. Convers. Manage. 51 (2010) 347–1353.
[10] M. Christensen, N. Johansson, Influence of mixture quantity on homogeneous charge compression ignition, SAE Paper 982454, 1998.
[11] E. Mancaruso, B.M. Vaglieco, Optical investigation of the combustion behaviour inside the engine operating in HCCI mode and using alternative diesel fuel, Exp. Therm. Fluid Sci. 34 (2010) 346–351.